Multiaperture Optical Switch for the NIF

M. Rhodes
C. Ollis
R. Bettenhausen
J. Trent
P. Biltoft

This article discusses the optical switch system for the National Ignition Facility (NIF). The NIF laser architecture is based on a multipass power amplifier to reduce cost and maximize performance. A key component in the laser design is an optical switch that “closes” to trap the optical pulse in the amplifier cavity for four gain passes and then “opens” to divert the optical pulse out of the amplifier cavity. The optical switch consists of a full-aperture Pockels cell that provides voltage control of the beam polarization and a reflecting–transmitting polarizer.

Figure 1 shows one of NIF’s 192 beamlines. During a NIF shot, an optical pulse enters the cavity from the transport spatial filter by reflecting off the polarizer. After the optical pulse passes through the Pockels cell, a precisely timed voltage pulse is applied to the Pockels cell so that the beam polarization is rotated 90° when it returns after reflecting from the LM1 mirror. The optical pulse then passes through the polarizer, reflects off the LM2 mirror, and passes back through the polarizer. Because voltage is still applied to the Pockels cell, the beam polarization is rotated back to its original polarization on this third pass through the Pockels cell. After the optical pulse passes, the voltage pulse starts to turn off. By the time the optical pulse returns again, no further rotation occurs. The beam reflects off the polarizer and exits the cavity, having passed through the main amplifier four times.

Optical switches are common in many types of lasers, such as Q-switched lasers and regenerative lasers. However, the size (40 × 40 cm), shape (square), and energy density (5 J/cm^2) of the NIF beams require an optical switch of unprecedented proportions. Commercially available, conventional Pockels cells do not scale to such

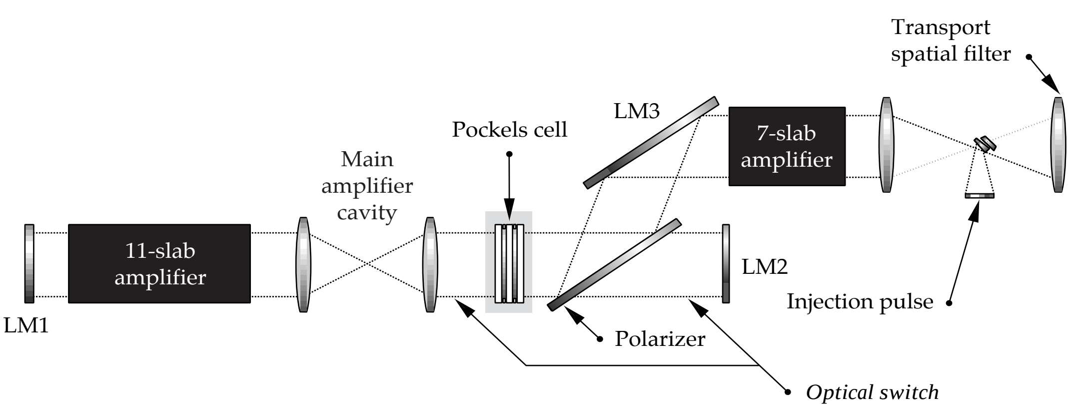

FIGURE 1. One of 192 beamlines of the NIF, showing the location of the optical switch system. (70-00-0299-0367pb01)

large apertures or the square shape required for close packing. The NIF optical switch is based on the plasma-electrode Pockels cell (PEPC). This article first reviews PEPC technology, then discusses the details of the NIF optical switch system, including the line replaceable unit (LRU), support structure, vacuum and gas systems, required assembly hardware, electronic systems required to operate the optical switch, and the computer control system.

Plasma Electrode Pockels Cell Technology

In any Pockels cell, polarization rotation of a transmitted laser beam occurs when an electric field is applied to an electro-optic crystal, inducing birefringence. In a conventional "ring-electrode" Pockels cell, the electric field is applied to a cylindrical rod of crystal via rings of metal deposited on the end faces of the rod. To obtain sufficient field uniformity across the active aperture, the length of the rod must be one to two times the diameter. This requirement poses a problem for Pockels cells with apertures larger than about 10 cm.

In a PEPC, the electric field is applied in a different way. A cloud of ionized gas (plasma) is formed by electric discharge on both sides of the crystal. The plasma is electrically conductive and transparent to the incoming laser beam. The plasma coats both sides of the crystal, allowing direct application of the required voltage (about 17,000 V in our case). The electric field is uniform across the entire aperture regardless of aperture shape or size.

PEPC technology was first invented at LLNL in the 1980s, but focused development of a PEPC to be used on a high-energy laser began in 1990. We progressed from a 27-cm-aperture PEPC to a 32-cm PEPC, then to the 37-cm PEPC that became a working part of the Beamlet laser (the scientific prototype for NIF). With the success of Beamlet and the Beamlet PEPC, we began working on a PEPC for NIF in 1995. The focus was to find a way to closely pack multiple apertures to meet the goals of the NIF conceptual design. Our work culminated in the NIF PEPC shown in Figure 2.

NIF PEPC Line Replaceable Unit

As with many other NIF components, the NIF PEPC is designed as a line replaceable unit (LRU) to enable rapid replacement and off-line repair. This is the smallest subarray of apertures that will be installed or removed from the NIF beamline. The PEPC LRU, shown in Figure 2, is a 4 × 1 module (four apertures high by one wide). A total of 48 PEPC LRUs will be required to provide optical switching for the 192 beamlines in NIF. Although the LRU integrates four apertures into one module, electrically it is divided into a pair of two-aperture PEPCs, one of which is shown in cross section on the right side of Figure 3. Also shown are the pulse generators that operate the PEPC. Each plasma pulser drives a pulse of current (~1000 A) through the low-pressure helium (~65 mTorr) on either side of the KDP crystals forming the plasmas. Once the plasmas cover both sides of the KDP, the switch pulser fires, applying the exact voltage (~17 kV) across the crystals required for 90° of polarization rotation.

The NIF PEPC is a complex piece of electro–mechanical–optical hardware that integrates various elements, including a four-aperture PEPC, a high-vacuum pumping system, a feedback-controlled gas-feed system, a support frame, and a three-point kinematic mounting system. Each of the four apertures in an LRU requires three large-aperture optical components: two fused silica windows and one plate of KDP. Each LRU contains eight windows and four KDP plates.

The Operational Core: A Four-Aperture PEPC

The operational core of the PEPC LRU is a four-aperture PEPC whose design is based on nine years of development and testing. All the PEPCs we have built have essentially the same construction. They are a sandwich structure made of an insulating midplane between a pair of housings. The midplane acts as a carrier for the KDP crystals. The housings, in conjunction with the windows, form sealed volumes covering

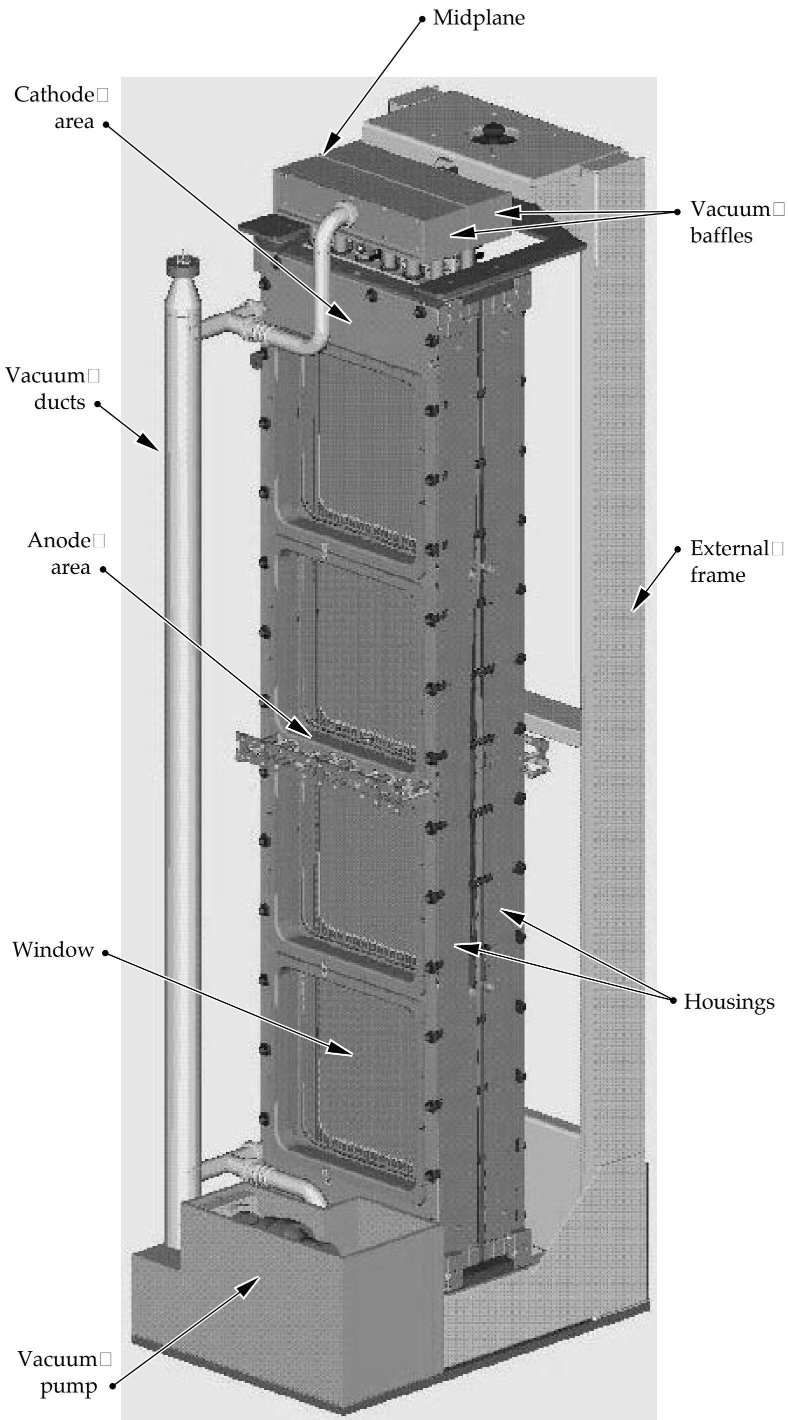

FIGURE 2. Each NIF PEPC line replaceable unit (LRU) is a 4 × 1 module. (08-00-1198-2240pb01)

the KDP surfaces. The plasma discharges required for PEPC operation are formed within these sealed volumes. The housings also act as mechanical members that support the midplane and allow for mounting of cathode-electrode assemblies, anode-electrode assemblies, vacuum baffle assembly, and silica windows.

An important difference between the Beamlet PEPC and the NIF PEPC is the choice of housing material. Housings in the Beamlet PEPC were fabricated from solid polyethylene. Although this material provided excellent insulation properties, the polyethylene proved difficult to machine to close tolerances. For NIF, the

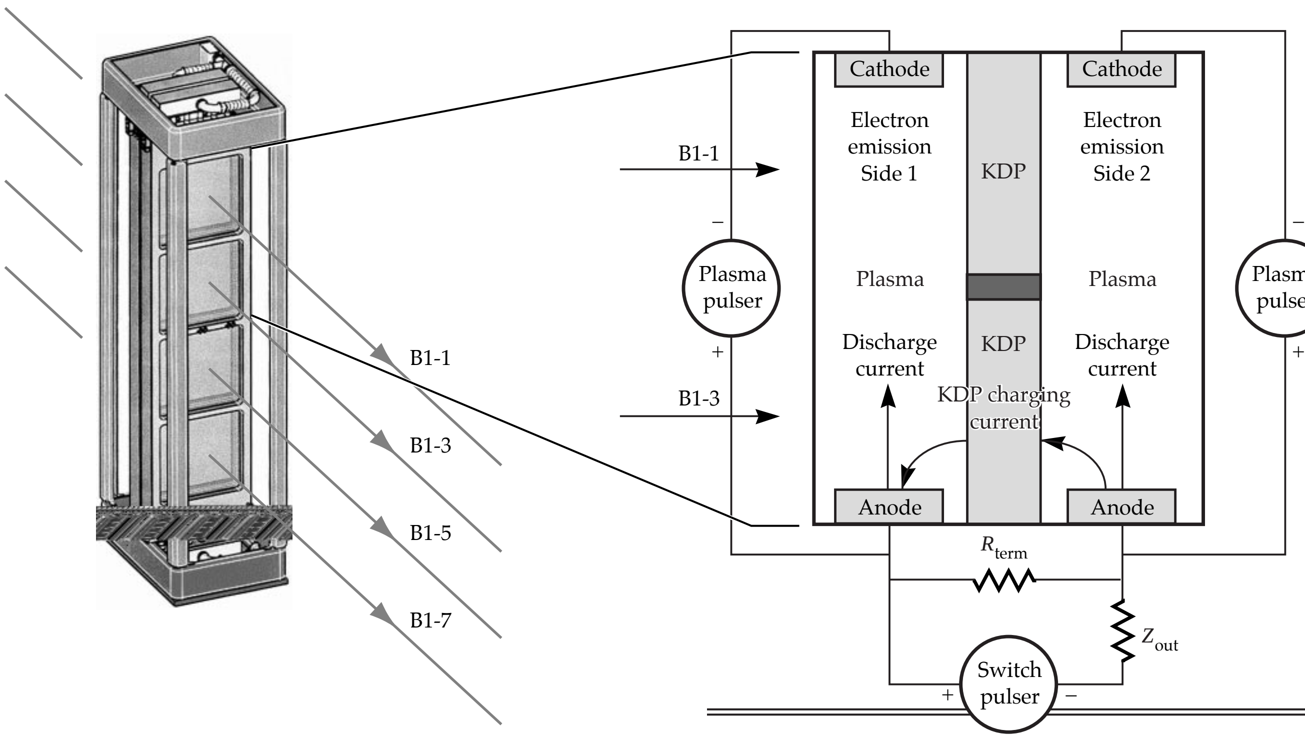

FIGURE 3. The LRU is electrically divided into a pair of two-aperture PEPCs, one of which is shown in cross section on the right. Also shown are the pulse generators that operate the PEPC. (70-00-0299-0368pb01)

PEPC housings are made from aluminum. Compared to polyethylene (or any other plastic), aluminum has superior strength and machinability. We take advantage of the higher strength by reducing the housing wall thickness enough to meet the aperture packing requirements for NIF. However, aluminum does not provide the required insulation between the discharge anode and cathode structures. They are insulated from the housing with plastic, and plasma is insulated from the aluminum walls by an anodic coating on the aluminum (Al_2O_3 insulator).

We have tested our design of the operational core by constructing an operational prototype shown in Figure 4. This device forgoes the external frame described below, but otherwise is a fully operational NIF 4 × 1 PEPC. We have tested the switching performance of the operational prototype in a four-beam polarimeter that illuminates each aperture with a low-fluence NIF-size laser beam. The experimental apparatus measures the fraction of light in two orthogonal polarizations, from which we can determine switching efficiency. If all the light is perfectly rotated exactly 90°, then the switching efficiency is 100%. In practice, there are always factors that cause less than perfect switching. Some examples are strain in the crystal, variations in applied voltage, and strain in the vacuum windows. Switching efficiency only includes losses due to polarization errors and does not include absorption in the crystal (about 5% per cm) or reflective losses from the optic surfaces. The NIF requirements are that the average switching efficiency across an entire aperture must be better than 99%, and that the minimum switching efficiency of any small spot must be greater than 98%. Results from the prototype show that each of the four apertures has an average switching efficiency of at least 99.8%, and the lowest small-area switching efficiency is 99.5%. Thus, the NIF requirements are easily met. We have determined that the dominant factor causing polarization error in our prototype is strain in the vacuum windows. Such strain is unavoidable because

FIGURE 4. Photograph of the prototype used to test our design of the operational core. This device has no external frame, but otherwise is a fully operational NIF 4 × 1 PEPC.
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of the atmospheric pressure difference across the windows. However, ensuring the flatness of the window support shelf in the housings can minimize the resulting polarization error.

Vacuum and Gas Feed System

The vacuum and gas feed system is required for plasma-discharge production. The vacuum system consists of a hybrid turbomolecular-drag pump. A single pump evacuates the entire LRU interior to the 10^{-6}-Torr range. The discharge volume is pumped through ports built into the cathode bases. These ports connect to the vacuum baffle structure. The baffles are insulators that keep the switch pulse from shorting out through the common vacuum system. The baffles connect to the turbo pump with a series of ducts. All turbo pumps in a cluster exhaust to a mechanically pumped foreline manifold.

The gas feed system injects the discharge gas near the anodes so the gas flows across the crystal faces. A constant pressure is maintained with a feedback-control system. We determined the operating pressure experimentally to optimize plasma uniformity, and the value is typically 65 mTorr in the NIF PEPC LRU. A group of gauges mounted on the vacuum ducting measures the pressure over various ranges. The high-vacuum base pressure is measured with a cold-cathode ionization gauge. The pumpdown from atmosphere is measured with a 0- to 1000-Torr capacitance manometer. The operating pressure is measured with 0- to 1-Torr capacitance manometer. This gauge provides feedback to the pressure controller that varies the output of a mass flow controller.

Support Frame and Kinematic Mounts

In the PEPC LRU, the operational core mounts into an L-shaped frame, as shown in Figure 5. The bottom of the support frame is an interface plate that incorporates all of the interfaces required between the PEPC LRU and the rest of the PEPC system. The interface plate includes feedthroughs for 4 plasma-pulse cables, 16 switch-pulse cables, 2 switch-pulse voltage monitors, gas input, foreline vacuum exhaust, vacuum gauge feedthroughs, and access to the turbo pump. The interface plate also seals to the NIF periscope structure after LRU insertion.

The PEPC LRU attaches to the periscope structure by a three-point kinematic mounting system that allows for safe, precise, ultraclean, repeatable positioning of the PEPC in the NIF beamline.

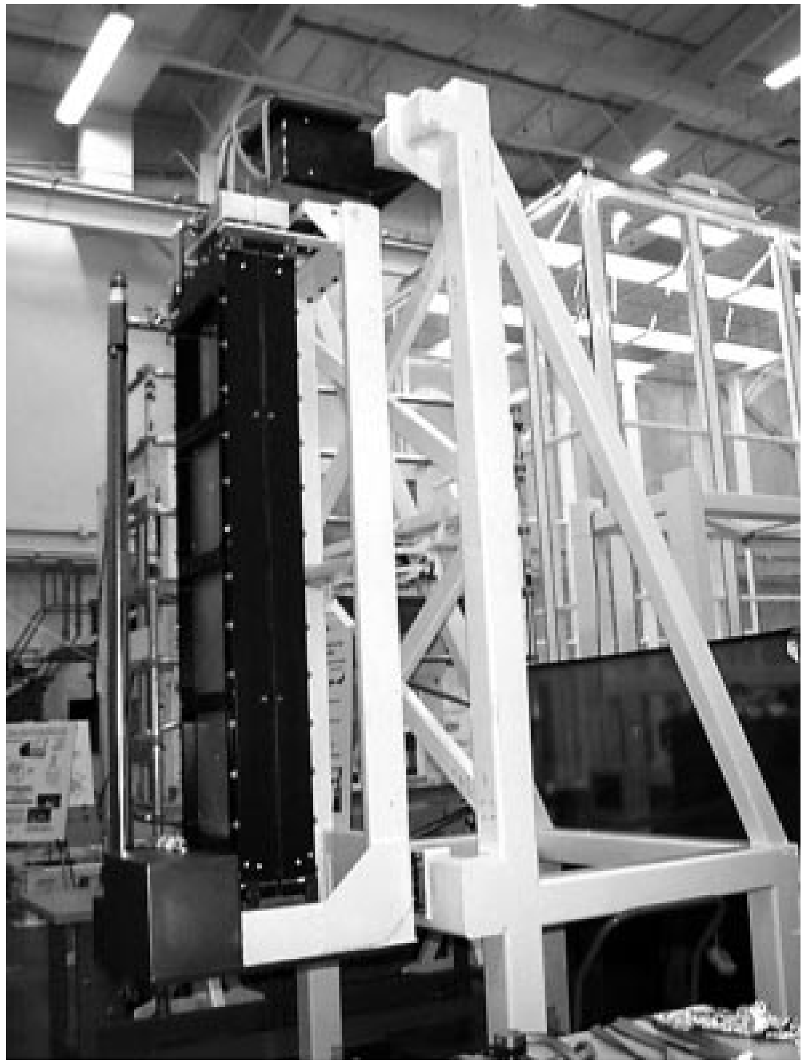

FIGURE 5. Prototype of the PEPC LRU mounted to a mockup section of periscope structure. (70-00-0299-0369pb01)

A ball mounted to the top of the LRU, as shown in Figure 6, is one of the three mounting points. When inserted into the periscope, the ball mates with a cone attached to the periscope frame. A closing "clamshell" mechanism captures the ball and keeps it in contact with the cone. The LRU essentially hangs from this device. The other two mounting points are a pair of V grooves, attached to each side of the LRU near the bottom, that mate with a pair of balls attached to the periscope frame.

The mounting system provides for precise and repeatable placement of an LRU in a NIF beamline. Each LRU must be interchangeable to any other location in the beamline. The requirement for positioning is ±1 mm in translation and ±120 μrad in rotation about the vertical axis. We have verified that our design meets these requirements by performing tests with the prototype assembly. Test results show that we achieved ±0.04 mm in translation and ±55 μrad in rotation about the vertical axis. The results are well within the NIF requirements.

Assembly Fixtures

The PEPC LRUs will be assembled in the NIF Optical Assembly Building (OAB). A dedicated area in the OAB will be configured specifically for PEPC assembly and testing. Because the PEPC LRUs contain

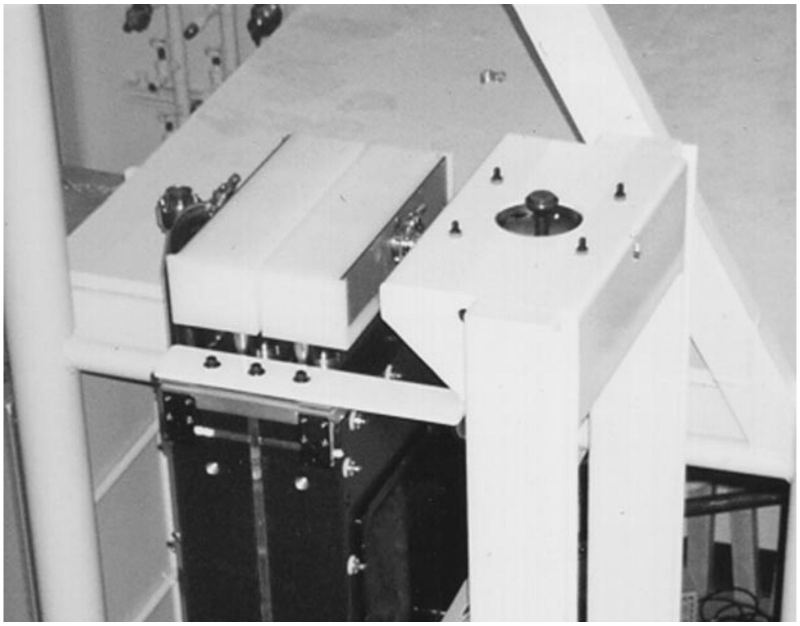

FIGURE 6. A ball mounted to the top of the LRU is one of the three mounting points by which the PEPC LRU attaches to the periscope structure.
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optics (windows and KDP crystals), the assembly procedure is designed to minimize contamination of optical surfaces.

We have designed and built a PEPC assembly fixture to facilitate assembly of PEPCs in a safe, ultraclean, and ergonomic manner. This device, shown in Figure 7, will be used in conjunction with an Ergotech motorized positioner. The Ergotech lifts and rotates the assembly fixture while the assembly fixture facilitates integration of the housings, midplane, and support frame.

The potting fixture, shown in Figure 8, is designed to control integration of KDP switch crystals into the glass midplane. The midplane has four apertures for crystals, which must be precisely positioned

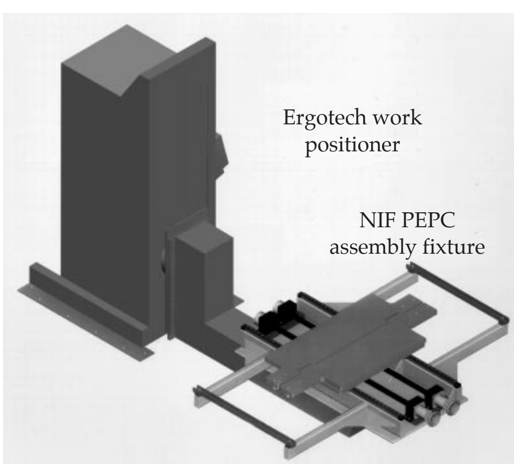

FIGURE 7. The PEPC assembly fixture will be used with an Ergotech motorized positioner to assemble PEPC LRUs in the Optical Assembly Building.
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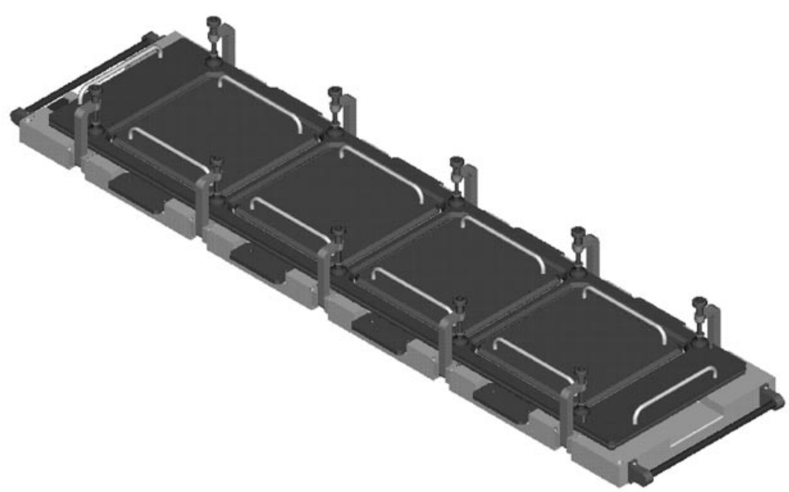

FIGURE 8. The potting fixture controls integration of KDP switch crystals into the glass midplane. (70-00-0299-0372pb01)

with respect to the midplane. Four gaskets that hold the crystals in the potting fixture are custom shaped to achieve precise positioning and provide a seal while potting. The crystals are potted with very-high-grade silicone rubber. The crystals are fragile and will fracture with minimal mechanical or thermal shock. The fixture and potting process minimize both mechanical and thermal loading of crystals.

PEPC Control System

The function of the PEPC control system is to provide remote control and monitoring of the PEPC subsystem during NIF operation. The system will control all the components of the PEPC system, including plasma pulsers, switch pulsers, vacuum and gas gauges, valves, and turbo and roughing pumps.

As with other segments of the NIF control system, the PEPC control system is based on front-end processors (FEPs) that connect upstream to supervisory software modules and downstream to input/output interfaces, as shown in Figure 9. Each cluster of 12 PEPC LRUs will require 3 FEPs. Because there are 4 clusters in NIF, the PEPC control system will have a total of 12 FEPs. The 3 FEPs per cluster divide the control duty for the PEPC subsystems. The first FEP controls the switch pulsers. The second FEP controls the plasma-pulser controls, monitors the individual gas and vacuum system on each LRU, and monitors the cluster-wide vacuum roughing system. The third FEP controls pulse diagnostics. It contains high-speed waveform digitizers for the acquisition of switch-pulse voltage and plasma-pulse current.

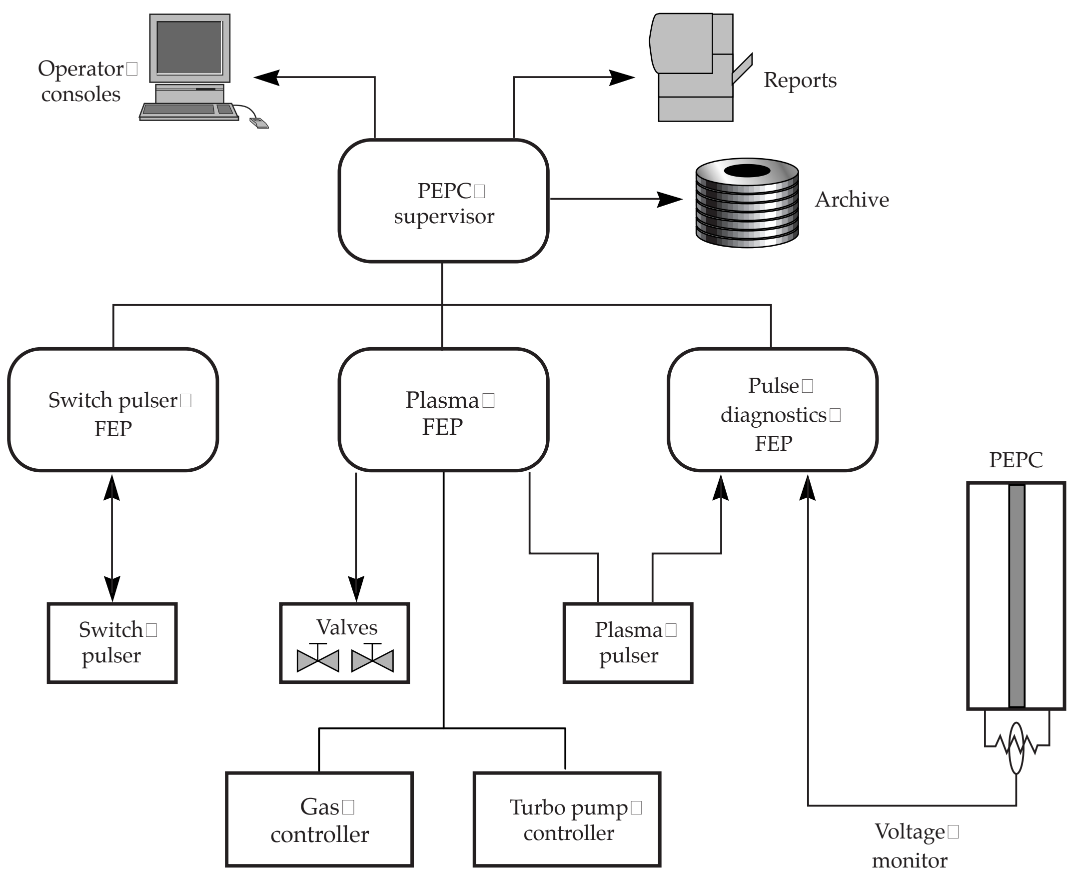

FIGURE 9. The PEPC control system. (70-00-0299-0373pb01)

During a NIF shot, the PEPC control system turns on the PEPC system, checks for normal operation of each LRU, fires the PEPC system every 5 s until a NIF shot occurs, and then turns the PEPC system off. The control system determines whether an LRU is firing properly by comparing the switch-pulse voltage waveform with a reference waveform, as shown in Figure 10. The actual waveform is subtracted from the reference. Any deviation in pulse timing or shape leads to a difference signal that is larger than the noise tolerance. The control system detects the difference and alerts the shot-control operators that a PEPC LRU is not working properly.

Conclusion

This article describes the NIF optical switch system, which enables multipass operation of the NIF laser amplifier. The NIF optical switch is based on a novel electro-optic device called the plasma electrode Pockels cell (PEPC). With PEPC technology, it is possible to construct Pockels cells with very large apertures. After proving the viability of large-aperture, PEPC-based optical switches on the Beamlet laser, we have designed and successfully tested a four-aperture PEPC for the NIF.

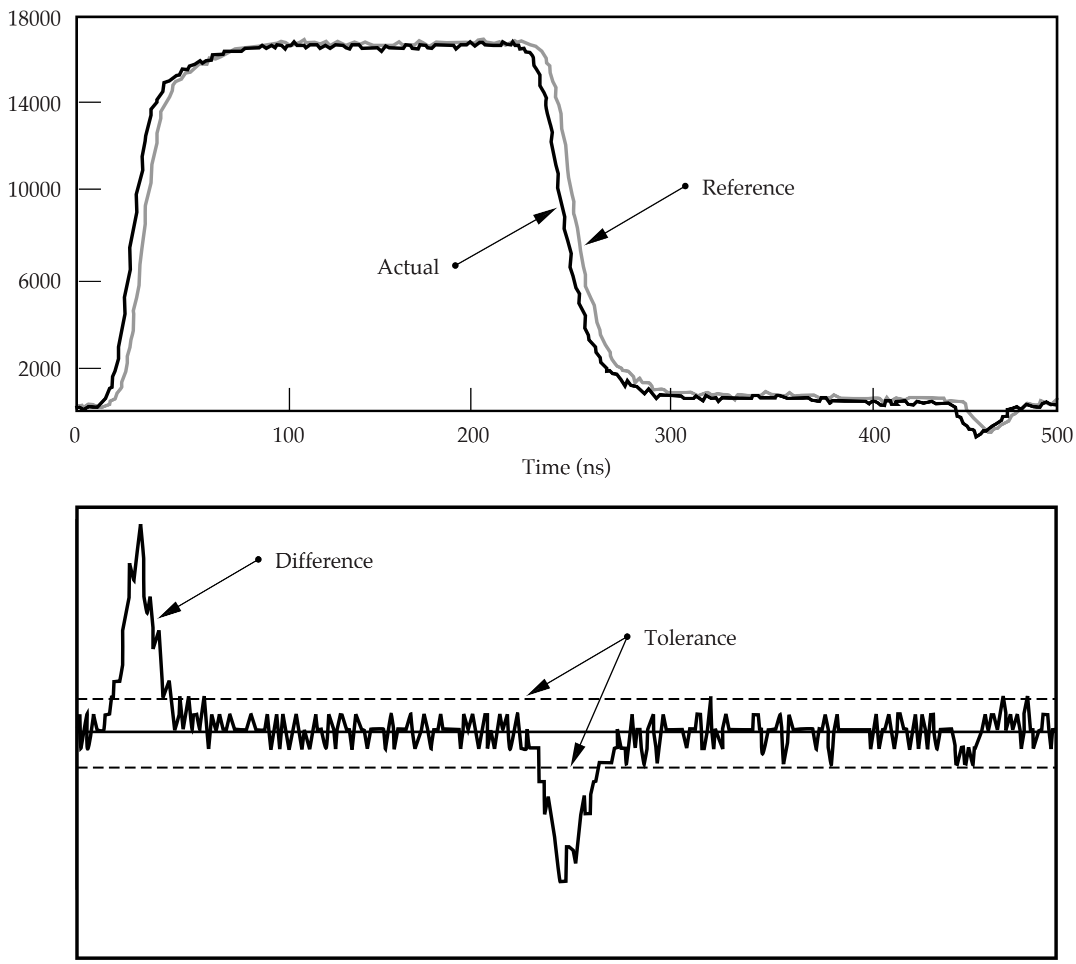

FIGURE 10. The PEPC control system determines whether an LRU is firing properly by comparing the switch-pulse voltage waveform with a reference waveform. (70-00-0299-0374pb01)